

Spin Glass and ferromagnetism in disordered Kondo lattice

S. G. Magalhães^a, F. M. Zimmer^a, P. R. Krebs^b

^a*Departamento de Física - UFSM*

97105-900 Santa Maria, RS, Brazil

^b*Instituto de Física e Matemática - UFPEL*

96010-900, Pelotas, RS, Brazil

Abstract

The competition among spin glass (SG), ferromagnetism and Kondo effect has been analysed in a Kondo lattice model where the inter-site coupling J_{ij} between the localized magnetic moments is given by a generalized Mattis model [5] which represents an interpolation between ferromagnetism and a highly disordered spin glass. Functional integral techniques with of Grassmann fields has been used to obtain the partition function. The static approximation and the replica symmetric ansatz has also been used. The solution of the problem is presented as a phase diagram temperature T versus J_K (the strength of the intra-site interaction). If J_K is small, for decreasing temperature there is a second order transition from a paramagnetic to a spin glass phase. For lower temperatures, a first order transition appears where solutions for the spin glass order parameter and the local magnetizations are simultaneously non zero. For very low temperatures, the local magnetizations becomes thermodynamically stable. For high J_K , the Kondo state is dominating. These results could be helpful to clarify the experimental situation of $CeNi_{1-x}Cu_x$ [1, 2].

Key words: Kondo lattice; spin glass; ferromagnetism

The effects of the disorder in the competition between RKKY interaction and the screening of localized moments due to the Kondo effect are quite novel. In particular, when the disorder and the RKKY interaction are combined to produce frustration. For instance, the alloy $CeNi_{1-x}Cu_x$ has been investigated by bulk methods [1, 2] showing that for low Ni content there is an antiferromagnetic phase. For high Ni content, the Kondo effect is dominating, it leads to a reduction of the magnetic moments. However, in the intermediated region, when the temperature is decreased, it appears a spin glass-like (SG) phase at T_f . The SG-like region becomes larger when Ni doping increases. There is the onset of the ferromagnetism (FE) at T_c , below the spin glass-like region ($T_c < T_f$).

Recently, a theoretical effort has been done to understand the emergence of a SG and ferromagnetic phases in a Kondo lattice model [4, 3] with a random Gaussian inter-site coupling among the localized spins. The partition function has been obtained within the path integral formalism by writing the spins operators as bilinear combinations of Grassmann fields. The inter-site coupling is treated using the Sherrington-Kirkpatrick (SK) approach. The obtained phase diagram shows the Kondo state, FE and SG solutions. Nevertheless, the FE solution appears always above the SG one in temperature ($T_c > T_f$). That is a clear indication that the high degree of frustration of the SK approach seems to be not adequate to tackle the experimental situation in the $CeNi_{1-x}Cu_x$.

We suggest that a approach where it is possible to interpolate from weak to strong frustration would be more adequate to address the experimental features of the $CeNi_{1-x}Cu_x$ alloy. That can be achieved by using the coupling between spins given by the generalization of the Mattis model [5]:

$$J_{ij} = \frac{J}{N} \sum_{\mu=1}^p \xi_i^\mu \xi_j^\mu, \quad (1)$$

where $\xi_i^\mu = \pm 1$ ($i = 1 \dots N$, $\mu = 1, \dots, p$) are random independent variables which follows the distribution

$$P(\xi_j^\mu) = 1/2\delta_{\xi_j^\mu, +1} + 1/2\delta_{\xi_j^\mu, -1}. \quad (2)$$

It is known that when $p = 1$ for classical spins with no magnetic field, it is recovered the limit of trivial disorder of the Mattis model with no frustration [5]. When $p = N$, in the thermodynamic limit ($N \rightarrow \infty$), one has a strong frustration similar to the S-K approach [6]. However, a method originally introduced to deal with complex systems [6], allows one to access the region between this two limits. In that approach, it is chosen configurations $\{\xi_i^\mu\}$ which minimizes the free energy. From that choice, it is possible to reconstruct the couplings J_{ij} to study the phase transitions present in the problem. In this method, $p = O(N)$ and the ratio $a = p/N$ is finite in the thermodynamic limit. Thus, a is a parameter controlling the degree of frustration.

Therefore, the purpose of this work is to combine both methods from Refs. [4, 6]. The static approximation and the replica symmetry ansatz has allowed

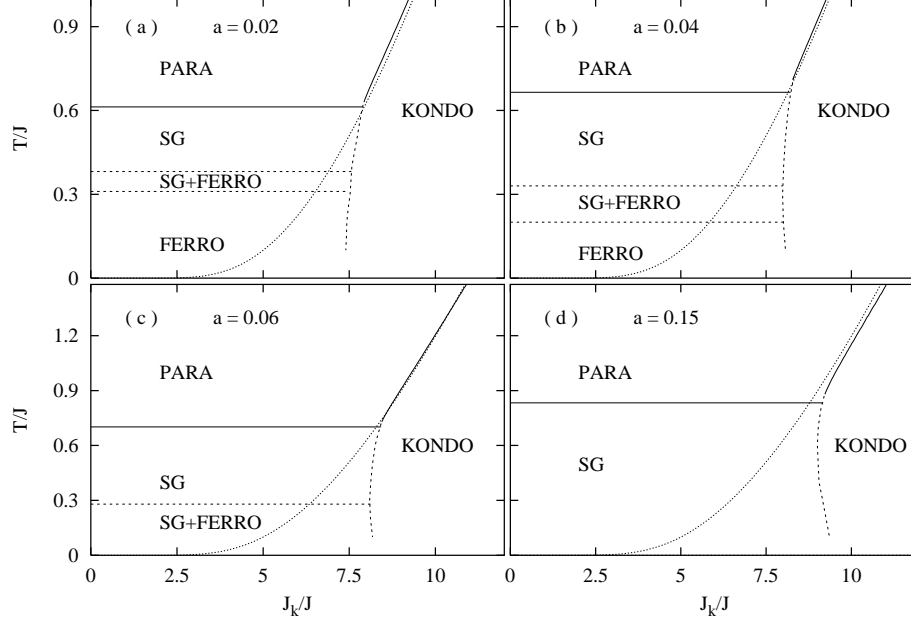


Figure 1: The phase diagram T/J versus J_K/J for several values of a showing the phases SG (spin glass), FERRO (ferromagnetism) and KONDO (the Kondo state). In the region SG+FERRO there is the coexistence between SG and FERRO. The first order transition is represented by the dashed line. The dotted means the "pure" Kondo temperature [4].

to find the free energy at mean field level in terms of SG order parameter q , the Kondo order parameter λ , the local susceptibility $\bar{\chi}$ [4] and $m^\mu = \frac{1}{N} \sum_i \xi_i^\mu < S_i >$. For $\mu = 1$, this parameter indicates the presence of Mattis states which is thermodynamically equivalent to ferromagnetism [6].

The model is the Kondo lattice [4] with the random intersite coupling J_{ij} given as Eq. (1):

$$H = \sum_{k,\sigma} \epsilon_k n_{k\sigma}^c + \sum_{i,\sigma} \epsilon_0 n_{i\sigma}^f + J_K \sum_i [S_{f,i}^+ s_i^- + S_{f,i}^- s_i^+] + \sum_{i,j} J_{ij} S_{fi}^z S_{fj}^z \quad (3)$$

The free energy is found as (the details will be provided elsewhere [7]) :

$$\beta f = 2\beta J_K \lambda^2 + \frac{a\beta\bar{\chi}}{2} \left[\frac{1 + \beta(q - \bar{\chi})}{1 - \beta\bar{\chi}} \right] + \frac{\beta}{2} (m^1)^2 + \frac{a}{2} \ln[1 - \beta\bar{\chi}] - \int_{-\infty}^{+\infty} Dz \ln \left\{ \int_{-\infty}^{+\infty} Dw \exp \left\{ \frac{1}{\beta D} \int_{-\beta D}^{+\beta D} dx \right. \right.$$

$$\langle \langle \ln[2(\cosh \frac{x+h}{2} + \cosh \sqrt{\Delta^2 + (\beta J_K \lambda)^2})] \rangle \rangle_{\xi} \} \quad (4)$$

where $\langle \langle \dots \rangle \rangle_{\xi}$ (the average over the ξ 's) can be found with Eq. (2), $Dz = dz \exp(-z^2/2)/\sqrt{2\pi}$, $\Delta \equiv \Delta(x, h) = (x - h)/2$ and

$$h = \sqrt{\beta \frac{2 - \beta \bar{\chi}}{1 - \beta \bar{\chi}}} w + \sqrt{\frac{\beta^2 a q}{1 - \beta \bar{\chi}}} z + \beta m^1 \xi. \quad (5)$$

In the Eq. (4), it has been used a constant density of states for the conduction electrons, $\rho(\epsilon) = \frac{1}{2D}$ for $-D < \epsilon < D$.

The Fig. (1) shows the result of the numerical analysis for the order parameters in a phase diagram temperature T/J versus J_K/J for several values of a . In the Fig. (1.a) ($a = 0.02$), for high temperature and small J_K , one gets paramagnetism. When the temperature is decreased, there is a second order transition to a SG phase. At low temperature appears a first order transition to the FE order with a coexistence region indicate as SG+FE in the Fig (1). For high J_K , appears a new order corresponding to the Kondo state. When the parameter a is increased (see Figs. (1.b) and (1.c)), the SG stability region is also increased. Finally, for $a = 0.15$ (see Fig. (1.d)), the FE solution disappears which recovers the results from Ref. ([4]). Therefore, if one associates the Ni content with both J_K and the degree of frustration a , the sequence of phases in Fig.1 has the correct order in temperature as the experimental results obtained by bulk methods [2]. That could also explain the increase of the SG-like region with the increase of Ni observed in the experimental diagram.

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